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RESEARCH MEMORANDUM

A STUDY OF INJECTION PROCESSES FOR LIQUID OXYGEN AND GASEOUS HYDROGEN IN A 200-POUND-THRUST ROCKET ENGINE

By Carmon M. Auble

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CLASSIFICATION CHANGED

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

January 9, 1957

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ERRATA

NACA Research Memorandum E56I25a

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January 9, 1957

Figure 11, page 28: In the key the symbol ◇ should represent chamber and characteristic lengths of 2 and 12.5 inches, respectively; the symbol ○ should represent chamber and characteristic lengths of 6 and 37.5 inches, respectively.

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RESEARCH MEMORANDUM

A STUDY OF INJECTION PROCESSES FOR LIQUID OXYGEN AND GASEOUS HYDROGEN IN A 200-POUND-THRUST ROCKET ENGINE

By Carmon M. Auble

SUMMARY

Six single-element injectors that systematically varied propellant spreading and mixing were compared using liquid oxygen and gaseous hydrogen in a 200-pound-thrust rocket engine. Characteristic velocity was measured over a range of oxidant-fuel weight ratios of approximately 2 to 7 at a total propellant flow of about 0.6 pound per second. Most of the experiments were made with propellants at an initial temperature of -320° F.

Characteristic velocity efficiency for all the injectors, except the parallel jets, approached 94 to 97 percent at the extreme fuel-rich mixture ratio. Injectors that mixed and spread the propellants had efficiencies exceeding 93 percent over the entire mixture range. An increase in hydrogen temperature from -320° to 80° F increased efficiency about 20 percent. For similar propellant treatment the combustor length for oxygen-hydrogen was about 0.2 to 0.5 times that needed to obtain comparable efficiencies with oxygen-heptane.

Fuel dispersion increased efficiency only slightly more than oxygen dispersion at comparable conditions. In both cases, the increase varied with mixture ratio and the treatment of the other propellant. Mixing had a relatively small effect on efficiency over the entire mixture range.

The data were compared with previous results for heptane-oxygen, and it was deduced that the combustion rates of both systems are controlled by physical processes such as atomization, evaporation, and diffusion, rather than by chemical kinetics.

INTRODUCTION

The oxygen-hydrogen propellant combination is of interest for long-range rocket missiles because of its high theoretical specific impulse.

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Some experimental engine data have been reported (refs. 1 to 4). High performance was obtained in relatively small combustors and in one investigation hydrogen was used as a regenerative coolant.

The work with oxygen-hydrogen propellants reported herein had two primary purposes: (1) to learn what injection processes are important in achieving high performance, and (2) to compare the results with similar data for other propellants in order to deduce the influence of propellant physical and chemical properties on injection requirements. 4040

The injection processes considered important from the standpoint of combustion efficiency and injector design are mixing and propellant dispersion or spreading. These processes are used to describe the primary functions of the injector. For example, mixing is a primary function when it is emphasized in an injector design although mixing occurs to some extent with any injection method.

This study was conducted in a 200-pound-thrust rocket engine with single-element injectors designed to emphasize the following schedule of injection processes:

(1) No mixing or spreading (dispersion)

(2) Spreading without mixing
- (a) Spreading of the oxygen only
- (b) Spreading of the hydrogen only
- (c) Spreading of both propellants

(3) Spreading with mixing
- (a) Mixing before spreading
- (b) Mixing after spreading

Total weight flow was held constant to ensure similarity between processes for the various injectors at the same mixture ratio. The relative importance of the processes was obtained by comparing characteristic velocity efficiencies of the injectors.

This study is similar to a previous one on oxygen and heptane reported in reference 5. The results are compared with that study for the significance of changes in physical and chemical properties.

APPARATUS AND PROCEDURE

Rocket Installation

The 200-pound-thrust rocket installation is shown schematically in figure 1. The uncooled rocket chambers were all 2 inches in diameter and varied in length from about 2 to 8 inches (characteristic lengths L^* 12.5 to 50 in.); most of the data was taken with 8-inch chamber lengths. An uncooled, convergent nozzle with a throat diameter of 0.78 inch was used. The design chamber pressure was 300 pounds per square inch. Ignition was accomplished with a spark plug mounted in the chamber wall.

Injectors

The single-element injectors are shown schematically in figure 2. The uncooled injectors were placed in the center of the injection plane. Centerline spacings of the jets and sheets were 0.30 inch for all injectors. The design conditions for injection velocity, total propellant momentum, and pressure drop are shown as a function of mixture ratio in figure 3. Injector g, which differs in arrangement from the others, was used only to examine the effect of fuel placement on efficiency.

Spray pictures for two injectors are shown in figure 4. Water was injected through the oxidant holes at a pressure drop of 100 pounds per square inch. Helium was injected through the fuel holes and its effect on the water spray is shown in the photographs. Increased helium flow improved atomization and spreading with all injectors. The momentum of a hydrogen jet was approximated by a helium pressure drop of 250 pounds per square inch, whereas, the velocity was approximated by a pressure drop of 10 pounds per square inch.

Instrumentation

Hydrogen-flow rates were measured with a venturi, and oxygen-flow rates with a rotating vane-type instrument. Pressures and thrust were measured with strain-gage transducers. Copper-constantan thermocouples were used to determine propellant temperatures. Instrument accuracy was evaluated statistically as described later.

Propellants

The propellants used were gaseous hydrogen and liquid oxygen. Hydrogen was used at -320° and 80° F, and oxygen at -320° F. The temperature of -320° F, the atmospheric boiling point of liquid nitrogen, was chosen for the following reasons: (1) the convenience of using liquid nitrogen as a coolant, and (2) the elimination of liquid-hydrogen handling problems. Hydrogen at -320° F more nearly approximates that hydrogen entering the injector of a regeneratively cooled engine than would liquid hydrogen. The oxygen was cooled to -320° F to minimize gas formation before injection.

Operating Procedure

For each run, the engine was started with a short oxygen lead, and then run at full propellant flow for about 2 seconds. Longer runs were not possible because of overheating of the uncooled rocket parts. Performance reached a constant value during this time. Runs were made over an oxidant-fuel weight-ratio range of about 2 to 7 (equivalence ratio of 0.25 to 0.88). Equivalence ratio r_e is defined as

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$$r_e = \frac{\text{Oxidant-fuel weight ratio}}{\text{Stoichiometric oxidant-fuel weight ratio}} = \frac{o/f}{7.95}$$

Total propellant weight flow was held at about 0.61 pound per second for all runs at an equivalence ratio above 0.35. Below this equivalence ratio, it was necessary to reduce weight flows because of limitations in the hydrogen-flow system. Since weight flow was constant and characteristic velocity varied with injector and mixture ratio, chamber pressure varied between 200 and 300 pounds per square inch.

Data Reduction

Cold hydrogen-flow calculations from venturi pressure data were made using pressure, volume, and temperature relations from reference 6.

Characteristic velocity c^* data were calculated for each run. Specific impulse I_s data were used as a check of the c^* evaluation. Characteristic velocity was calculated from the following equation

$$c^* = P_c A_t g/w$$

where

P_c chamber pressure, lb/sq in. abs

A_t nozzle throat area, sq in.

g mass conversion factor, 32.2 ft-lb/(lb)(sec^2)

w total propellant flow rate, lb/sec

Specific impulse was calculated from

$$I_s = F/w$$

where F is thrust in pounds.

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The error limits on experimental characteristic-velocity data were calculated using the statistical methods described in reference 7. The calculations were based on standard deviations of instrument calibration readings over a period of time. They include instrument and reading errors for static instrument operation. Dynamic errors may have been somewhat larger because of greater difficulty in reading data that oscillated about a mean value. Error limit ranges shown on the data curves are 95-percent probability limits.

Because uncooled chambers were used, the data were not corrected for heat-transfer losses.

Theoretical Performance

Theoretical characteristic velocity and specific impulse for hydrogen - liquid oxygen systems are shown in figure 5. These data were obtained from reference 8 (table II, figs. 4 and 5). Corrections are shown for gaseous hydrogen, and the data are for a convergent nozzle.

RESULTS AND DISCUSSION

Characteristic velocity is shown as a function of mixture ratio in figure 6 for injectors (a) to (f). Also shown are characteristic velocity and specific impulse efficiencies (percent of theoretical values). Figure 7 summarizes the c^* efficiencies; for comparison, the data of reference 5 for oxygen-heptane are also plotted. Best efficiency was always obtained at the richest mixture tested ($r_e = 0.25$; o/f = 2.0). This mixture is richer than those for maximum theoretical characteristic velocity ($r_e = 0.35$; o/f = 2.8) and maximum theoretical specific impulse ($r_e = 0.4$; o/f = 3.2).

Injector Efficiencies

<u>No spreading or mixing</u>. - The parallel-jets injector (fig. 7(a)), representing minimum spreading and mixing, gave the lowest efficiencies, 69 to 83 percent. These values are 30 to 40 percent higher than those obtained for oxygen-heptane in reference 5.

<u>Effect of propellant spreading</u>. - Fuel spreading produced only a slightly larger efficiency increment than oxygen dispersion. The effects are shown in figures 8 and 9, where the shaded areas represent the efficiency increases for oxygen dispersion and hydrogen spreading, respectively. Similar data for oxygen-heptane (ref. 5) are also shown for comparison. It is apparent that the effects of propellant spreading depend on the mixture ratio and the treatment given the other propellant.

The efficiency with oxygen atomization when the fuel was not dispersed (fig. 8(a)) decreased with an increase in equivalence ratio to about 0.5 to 0.6 and then increased. The initial decrease may be due to the spreading of oxygen away from the vicinity of the hydrogen jet. The reason for the increase following is not so apparent. The decreasing momentum of the hydrogen jet coupled with improved oxygen atomization could permit the flame front to move nearer the injector and so improves mixing because of combustion turbulence.

When the fuel is dispersed (fig. 8(b)), the efficiency with oxygen atomization increases with equivalence ratio. This may be interpreted simply as the result of continual increase in interfacial area together with improved oxygen atomization. 4040

The effect of fuel spreading when the oxygen was not atomized (fig. 9(a)) decreased the efficiency continually as the equivalence ratio increased. This behavior probably reflects the decreased dispersion of hydrogen as momentum decreases.

As might be expected, fuel spreading in the presence of dispersed oxygen (fig. 9(b)) produced about the same effect as the reverse treatment (fig. 8(b)) and for the same reasons.

Spreading both propellants (fig. 7(d)) substantially decreased the dependence of efficiency on mixture ratio (91 to 97 percent). The individual effects of propellant spreading were not additive in view of their strong dependence on environment.

Effect of mixing. - Mixing the propellants either before or after spreading (figs. 7(e) and (f)) essentially eliminated the dependence of efficiency on mixture ratio (93 to 96 percent). As shown in figure 10, mixing produced a very small increase in efficiency. This result is in harmony with the large effects of propellant spreading. With essentially gaseous propellants of low molecular weight, the diffusion rates are so large that spreading is accompanied by appreciable mixing. Forced mixing, therefore, can have only a minor effect on efficiency. This complicated spreading-mixing phenomenon probably explains why the individual spreading effects were nonadditive.

Another way to evaluate the relative effects of spreading and mixing on c^* efficiency is to measure these effects as a function of combustor length. Figure 11 shows the data from such experiments.

The relatively small influence of mixing on combustion efficiency even at a combustor length of 2 inches agrees with the previous discussion. Comparison of the parallel-jet and parallel-sheet data again shows the relatively large effects of propellant spreading.

Effect of hydrogen temperature. - Figure 12 shows the c* efficiency of the parallel-jets injector for a hydrogen inlet temperature of 80° F. A 400° F increase in initial fuel temperature improved efficiency about 20 percent.

The reactivity of the mixture probably increased with the increase in initial temperature and so improved the heat-release rate near the injector. In addition, the higher temperature undoubtedly improved dispersion and diffusion of the fuel, and decreased the heating requirements for ignition. The net result would be better propellant preparation for burning, which could compensate for any reduction in stay-time and mixing that might have occurred because of the higher axial injection velocity of the fuel.

Although this test of hydrogen-temperature effects was limited in scope, there is no apparent reason to believe that efficiency would be reduced in any case with an increase of injection temperature.

Effect of fuel placement. - The effects of placing the hydrogen outside the oxygen are shown in figure 13. Efficiency over the entire mixture-ratio range is less than for the parallel-jets injector. In this case, apparently, a major portion of the fuel can diffuse away from the reaction zone without reacting. With a large number of elements this effect would probably be negligible except at the periphery of the injection plate where asymmetric fuel placement might occur.

Operational Characteristics

Starting and stability. - Starts were always smooth with the propellants when an oxygen lead of about 0.1 second was used. The injectors exhibited little instability that could be detected. One photograph showed some rotary screaming (high-frequency pressure oscillations) with the impinging-sheets injector. It is possible that this screaming occurred at other times, but was not detected. Occasional chugging was observed at low oxygen pressure drops (i.e., about 50 lb/sq in.) with all injectors.

Burnouts. - The three highest performing injectors (impinging sheets, impinging jets, and parallel sheets; fig. 7) heated chambers very rapidly, often burning them out. It is possible that undetected rotary screaming was responsible for this high heat transfer to the chamber. Injector damage was seldom experienced with any of the injectors.

Comparison of Oxygen-Hydrogen and Oxygen-Heptane Systems

The effects of propellant properties on c^* efficiency can be deduced by comparing the results of this investigation with those of reference 5 for oxygen-heptane. Such a comparison is shown in figure 14. The efficiency increments from figures 8 to 10 have been normalized by dividing by the difference between theoretical and actual characteristic velocity for the parallel-jets injector. In this way the large difference in base efficiency (parallel jets) for the two systems does not interfere with the comparison. For purposes of discussion, the normalized 4040
parameter is called the "improvement factor."

Comparison of base efficiencies. - The large difference in base efficiencies between oxygen-hydrogen and oxygen-heptane (30 to 40 percent) might be due to the higher reactivity of the hydrogen system or the higher diffusion rate of hydrogen. Although the laminar flame speed of oxygen-hydrogen is considerably higher than oxygen-heptane, the ratio of diffusion rates is even greater. This fact leads to the deduction that fuel-physical-property differences are primarily responsible for the observed differences in c^* efficiency. This argument is further supported by the following discussion on propellant spreading. The difference in fuel physical states may not enter the comparison because the enthalpy rise required for hydrogen entering at -320° F is greater than that required to vaporize and heat heptane to the respective ignition temperatures. Because of the phase change with heptane, however, the heating rates of the two fuels could be quite different.

Propellant spreading. - The improvements from oxygen atomization and fuel dispersion for the two propellant systems are compared in figures 14(a) to (d). The improvement factors for oxygen-hydrogen, unlike those for oxygen-heptane, depend strongly on mixture ratio and treatment of the other propellant. This difference can be explained by assuming that fuel vaporization is the rate-controlling step in oxygen-heptane combustion, and propellant diffusion, the rate-controlling step in oxygen-hydrogen combustion. The latter would depend on mixture ratio and interfacial area between propellants.

Dispersion of both propellants (fig. 14(e)) produces about the same improvement factor for both systems. Such behavior would not be expected if chemical kinetics were rate-controlling for the oxygen-hydrogen system, which supports the deduction that physical processes control both systems.

For the oxygen-heptane system, fuel atomization was roughly three times as effective as oxygen atomization, whereas these effects were nearly the same for the oxygen-hydrogen system. It is concluded that as the physical properties (volatility, state, diffusion rate) of the fuel and oxidant become similar so do the effects of atomizing or spreading each propellant.

Propellant mixing. - The effects of mixing are shown in figures 14(f) and (g), and are about the same for both systems. For well-atomized systems, therefore, induced mixing only supplements that obtained from diffusion and combustion turbulence.

With oxygen-heptane (ref. 5), mixing did reduce combustor volume requirements. This was not the case in the present study (fig. 11). Apparently, the diffusion of hydrogen is so rapid at combustion temperatures that forced mixing has only a minor influence on combustion rate.

Combustor volume requirements. - The data of figure 11 when compared with the extrapolated combustor velocity curves of reference 5 provide an estimate of the relative combustor volumes required by the two systems at comparable efficiencies.

With no spreading or mixing, oxygen-hydrogen required not more than half the volume of oxygen-heptane.

When the propellants were spread and mixed, the ratio of combustor volumes was not more than about 0.2. Such a reduction in combustor volume could mean a lighter powerplant and possibly alleviation of the cooling problem with the oxygen-hydrogen system.

SUMMARY OF RESULTS

Injection processes for gaseous hydrogen and liquid oxygen at a temperature of -320° F were studied using single-element injectors in a 200-pound-thrust rocket engine. Six injectors that varied spreading and mixing were used. Characteristic velocity was measured over an oxidant-fuel weight ratio of about 2 to 7 at a propellant weight flow of about 0.6 pound per second. Chamber pressure varied from 200 to 300 pounds per square inch absolute. The results are summarized as follows:

1. Injectors that mixed and spread the propellants had characteristic-velocity efficiencies of at least 93 percent over the entire mixture range.

2. Injectors, which spread either the oxygen or fuel alone, had characteristic-velocity efficiencies which varied from 78 to 98 percent over most of the mixture range; spreading both propellants increased the efficiency to at least 91 percent over the entire mixture range.

3. With the parallel-jets injector (no induced mixing or spreading), characteristic-velocity efficiency varied from 69 to 83 percent.

4. For all but one of the injectors, characteristic-velocity efficiency approached 95 percent as mixture ratio (oxygen/fuel) approached 2.0.

5. An increase in hydrogen temperature from -320° to 80° F, increased efficiency about 20 percent for the parallel-jets injector.

6. A decrease in chamber length from 8 to 2 inches had little effect on performance of injectors which spread both propellants whether or not mixing was induced.

7. Comparison of the results with those obtained in a previous study of oxygen-heptane showed that the relative effects of mixing and spreading on characteristic-velocity efficiency can be qualitatively predicted by considering propellant physical properties, and that with adequate preparation oxygen-hydrogen requires about 0.2 to 0.5 the combustor volume of oxygen-heptane. 4040

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 26, 1956

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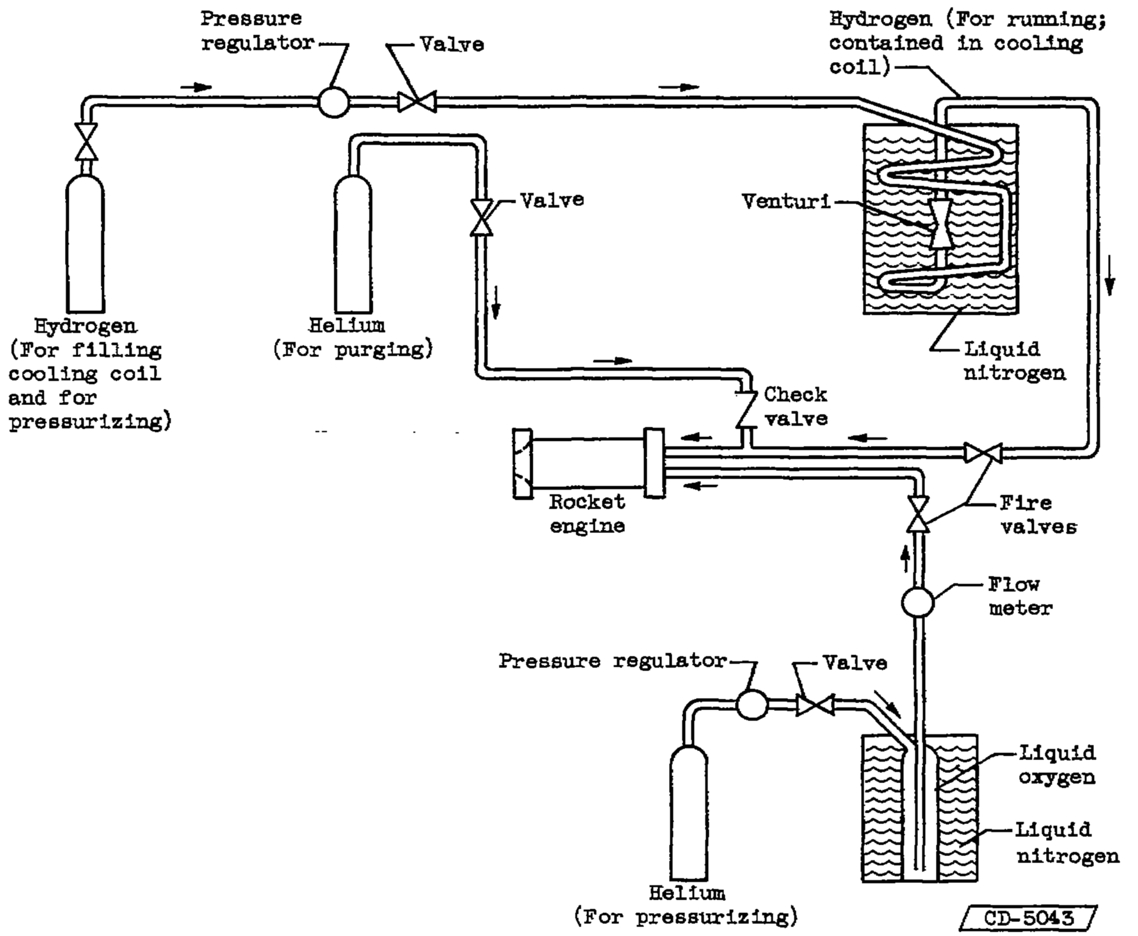

Figure 1. - Schematic diagram of gaseous hydrogen - liquid oxygen rocket installation.

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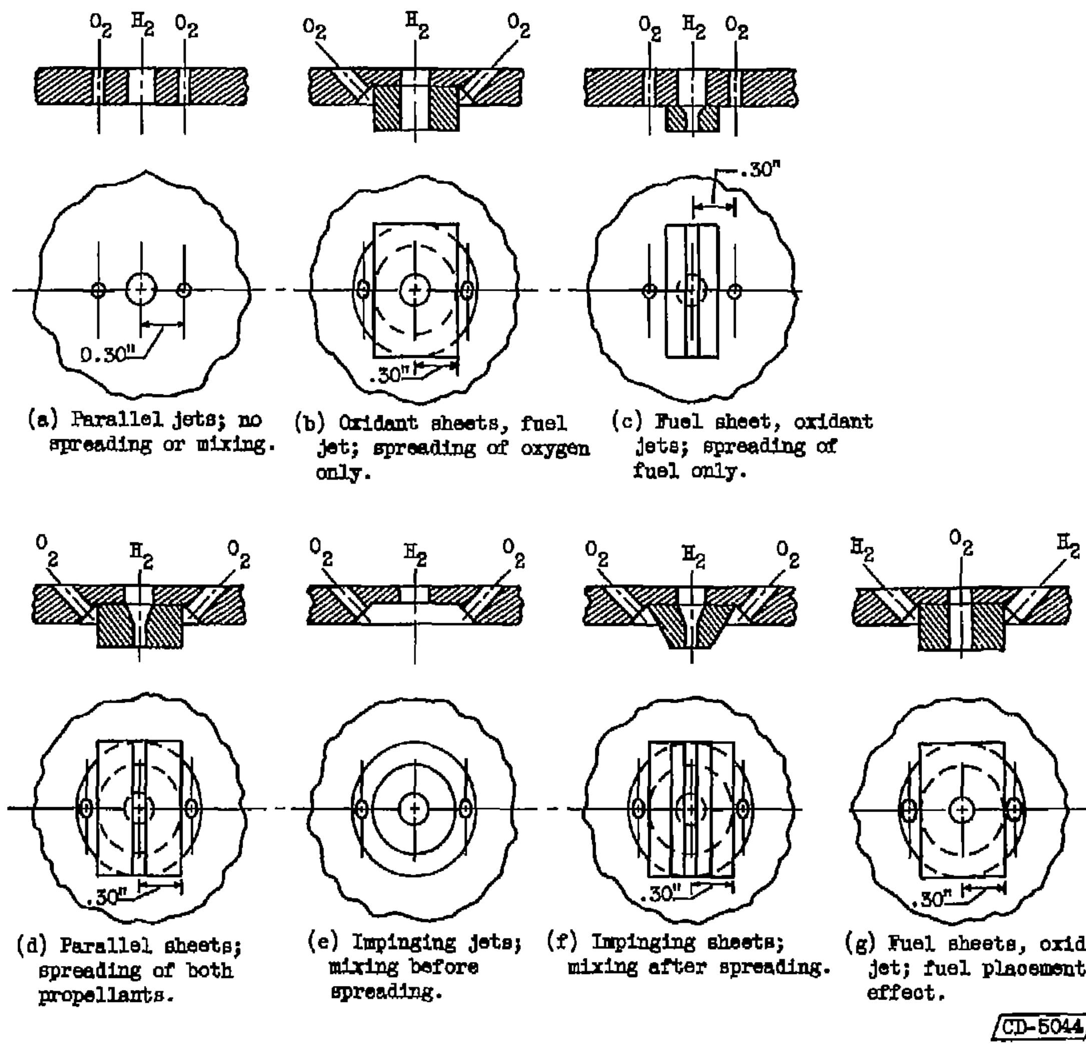

(a) Parallel jets; no spreading or mixing.

(b) Oxidant sheets, fuel jet; spreading of oxygen only.

(c) Fuel sheet, oxidant jets; spreading of fuel only.

(d) Parallel sheets; spreading of both propellants.

(e) Impinging jets; mixing before spreading.

(f) Impinging sheets; mixing after spreading.

(g) Fuel sheets, oxidant jet; fuel placement effect.

Figure 2. - Schematic diagrams of injectors designed to emphasize various injection processes. Fuel slots, 0.08 inch wide. Injectors (a) to (f): hydrogen-hole diameter, 0.228 inch; oxygen-hole diameter, 0.935. Injector (g): hydrogen-hole diameter 0.181; oxygen-hole diameter, 0.132.

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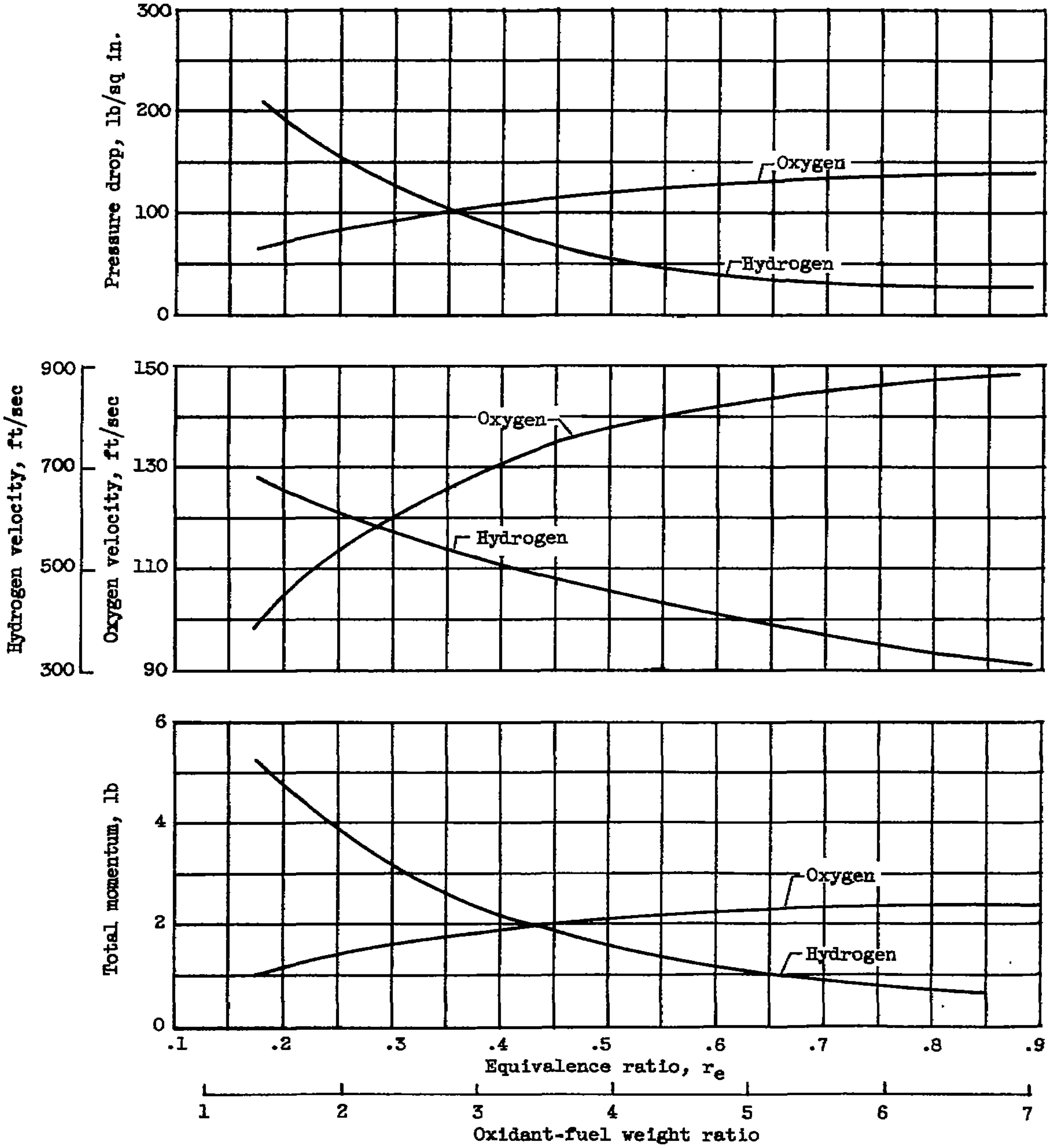

Figure 3. - Injector design conditions for pressure drop, injection velocity, and total propellant momentum.

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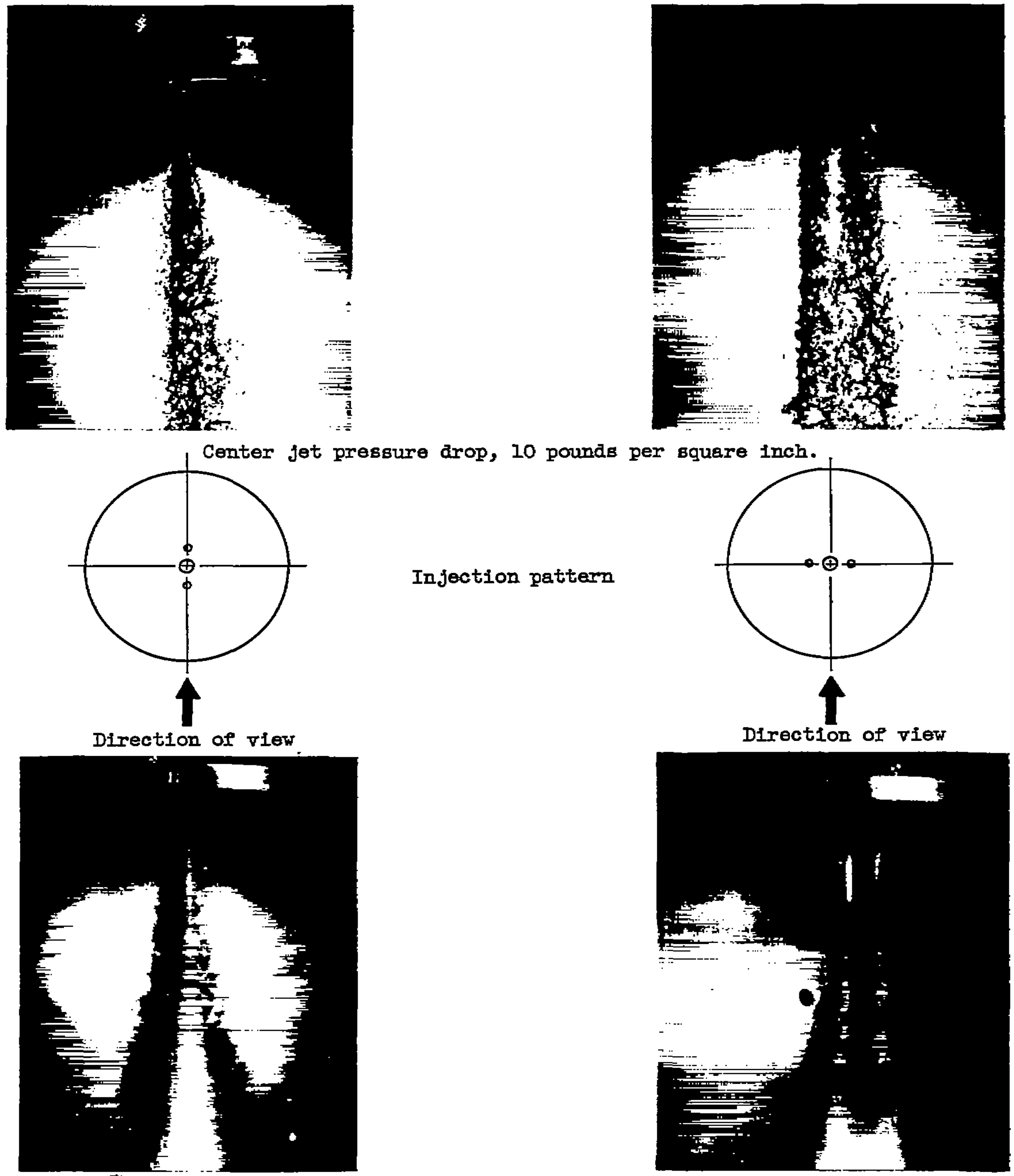

CD-5045
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(a) Parallel-jets injector.

Figure 4. - Spray photographs with water flow through oxygen orifices at a pressure drop of 100 pounds per square inch and helium flow through hydrogen orifices at pressure drops of 10 and 250 pounds per square inch.

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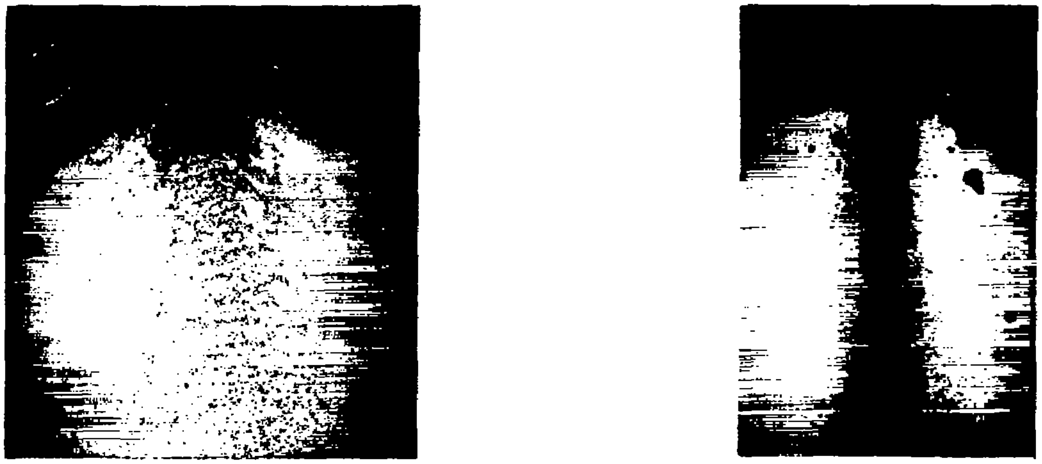
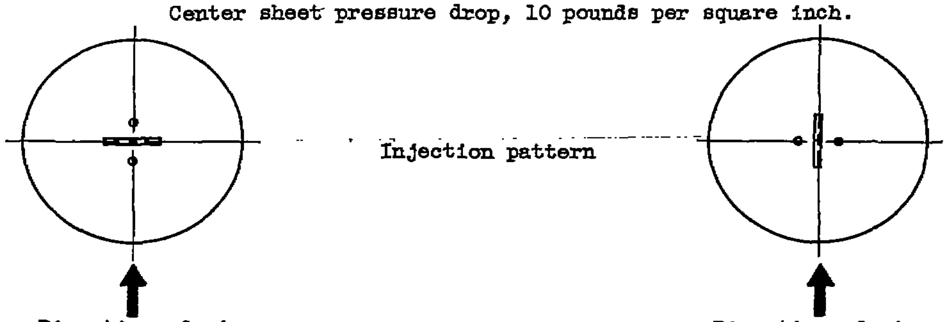


Center sheet pressure drop, 10 pounds per square inch.



Center sheet pressure drop, 250 pounds per square inch. CD-5046
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(b) Impinging-sheets injector.

Figure 4. - Concluded. Spray photographs with water flow through oxygen orifices at a pressure drop of 100 pounds per square inch and helium flow through hydrogen orifices at pressure drops of 10 and 250 pounds per square inch.

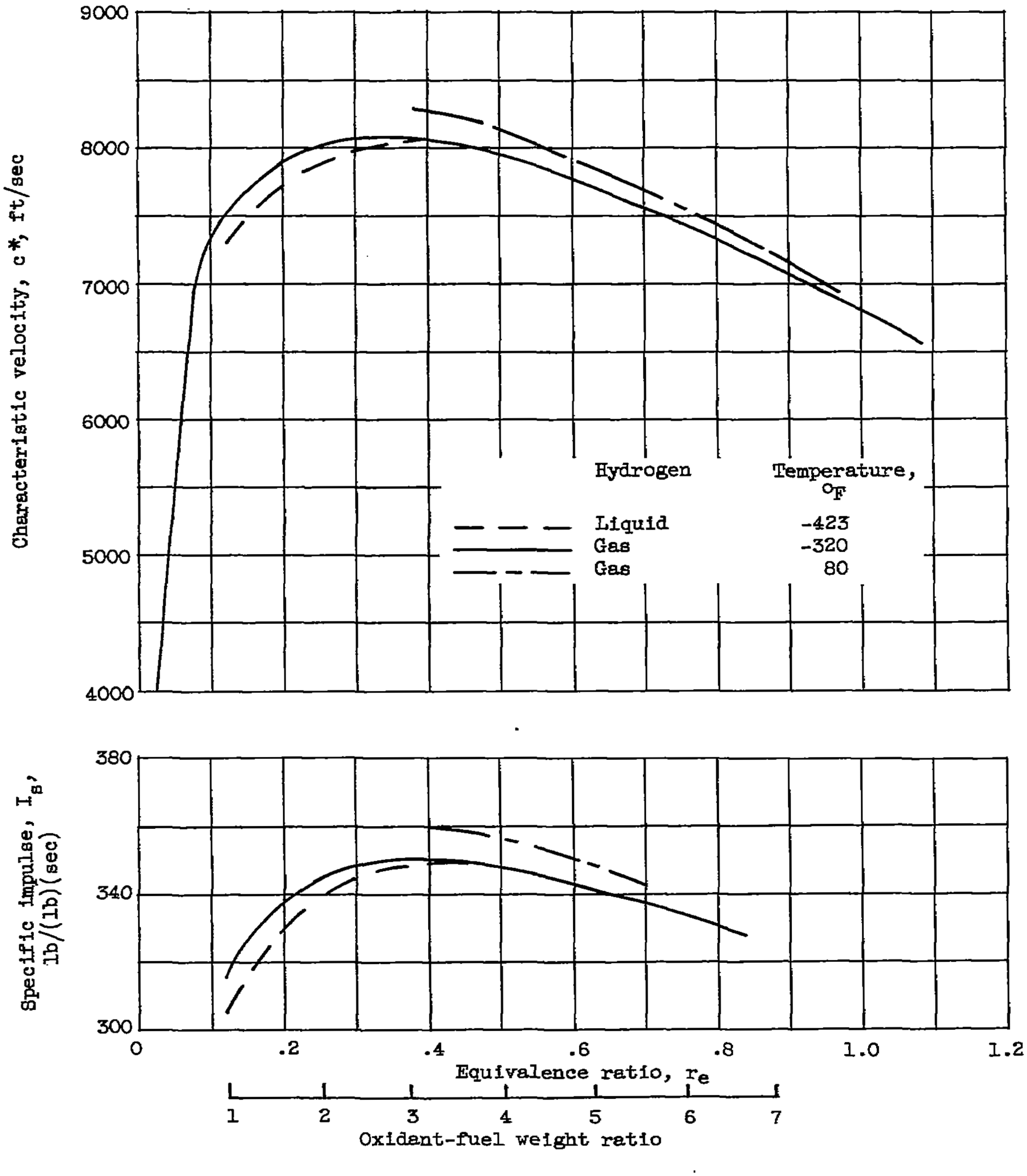

Figure 5. - Theoretical characteristic velocity and specific impulse for hydrogen-oxygen propellant system at 300 pounds per square inch absolute with chamber-pressure nozzle-area ratio of 1 and equilibrium expansion.

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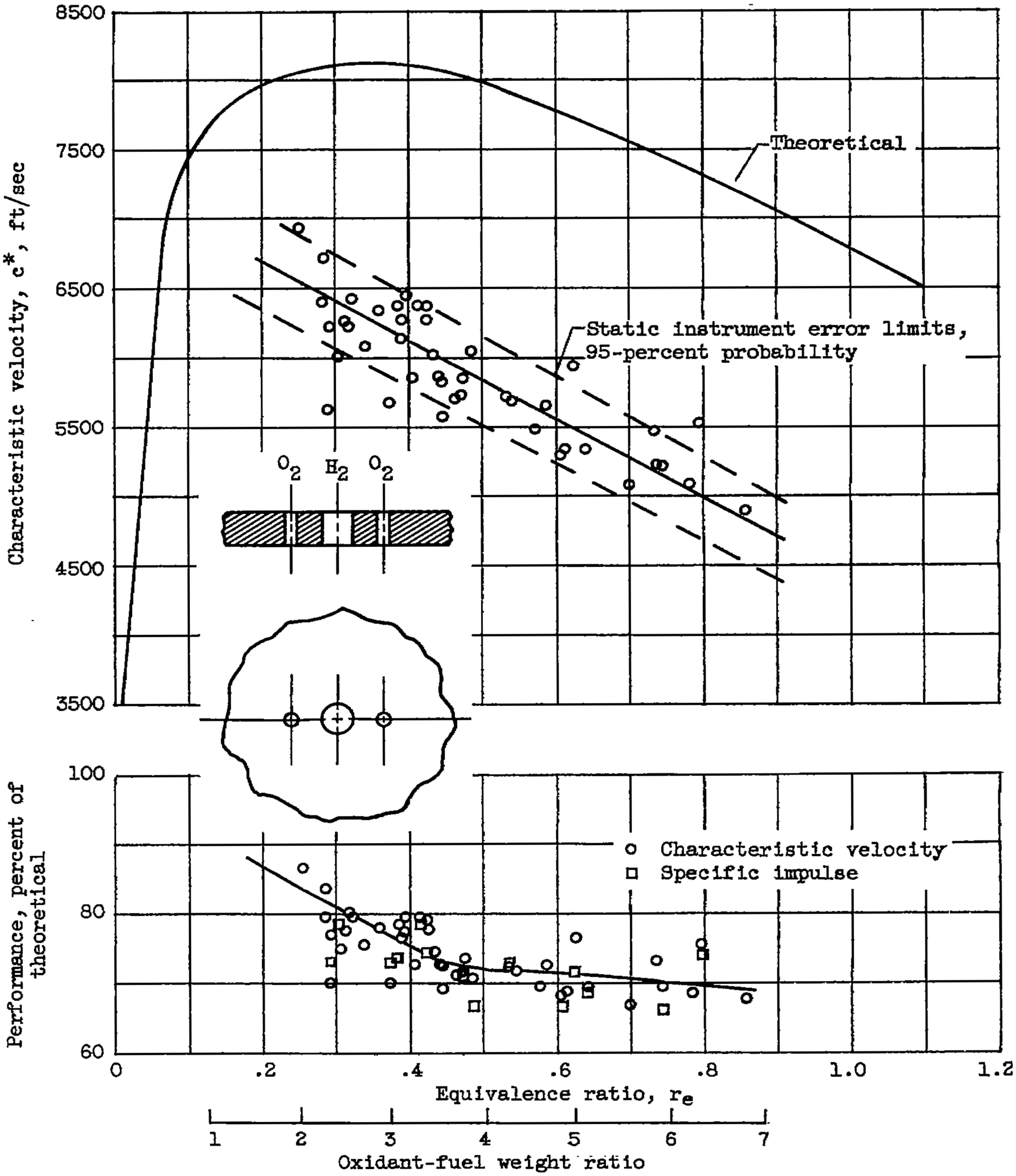

(a) Parallel-jets injector; no spreading or mixing.

Figure 6. - Engine performance with combustion chamber having characteristic length of 50 inches.

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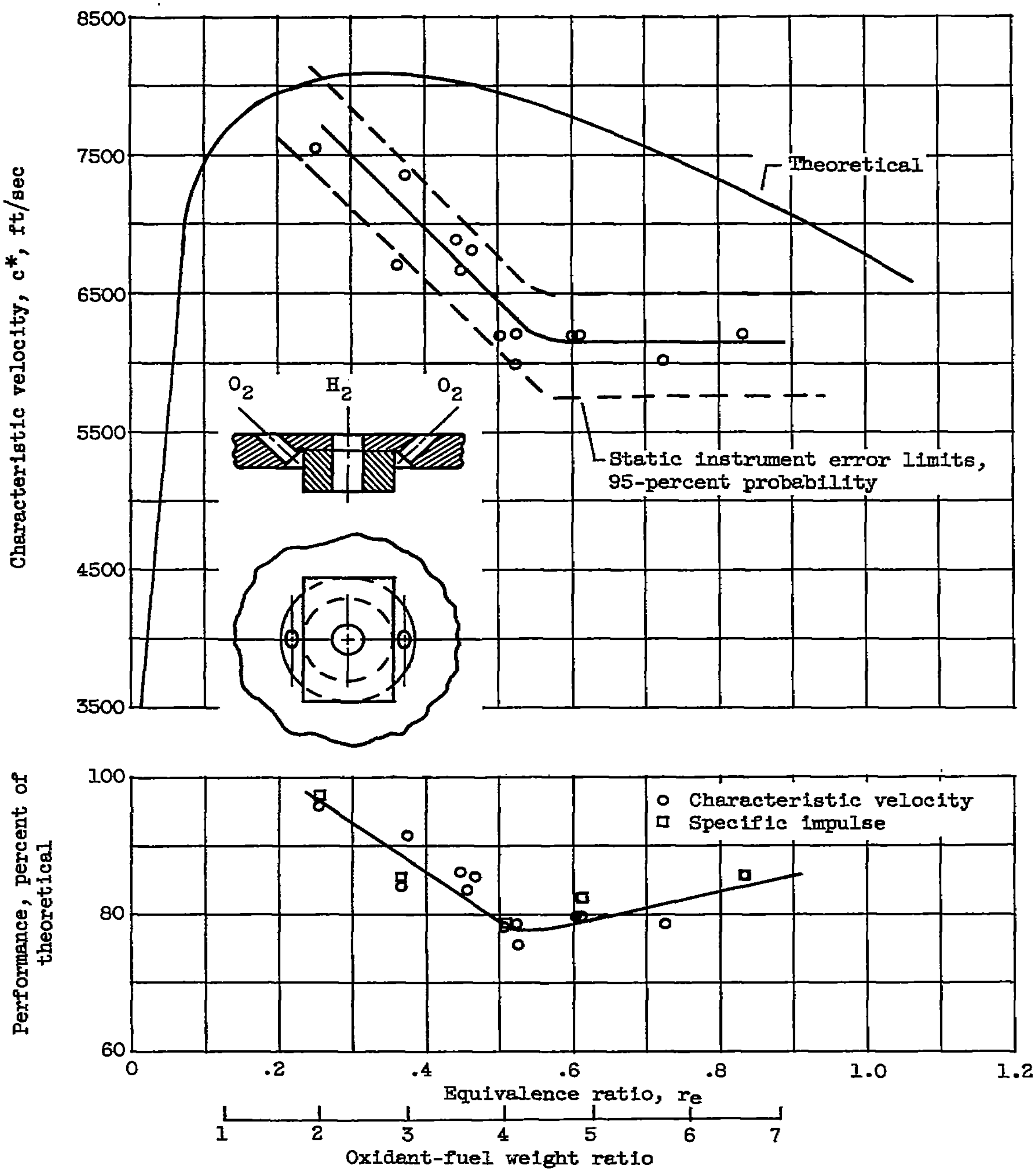
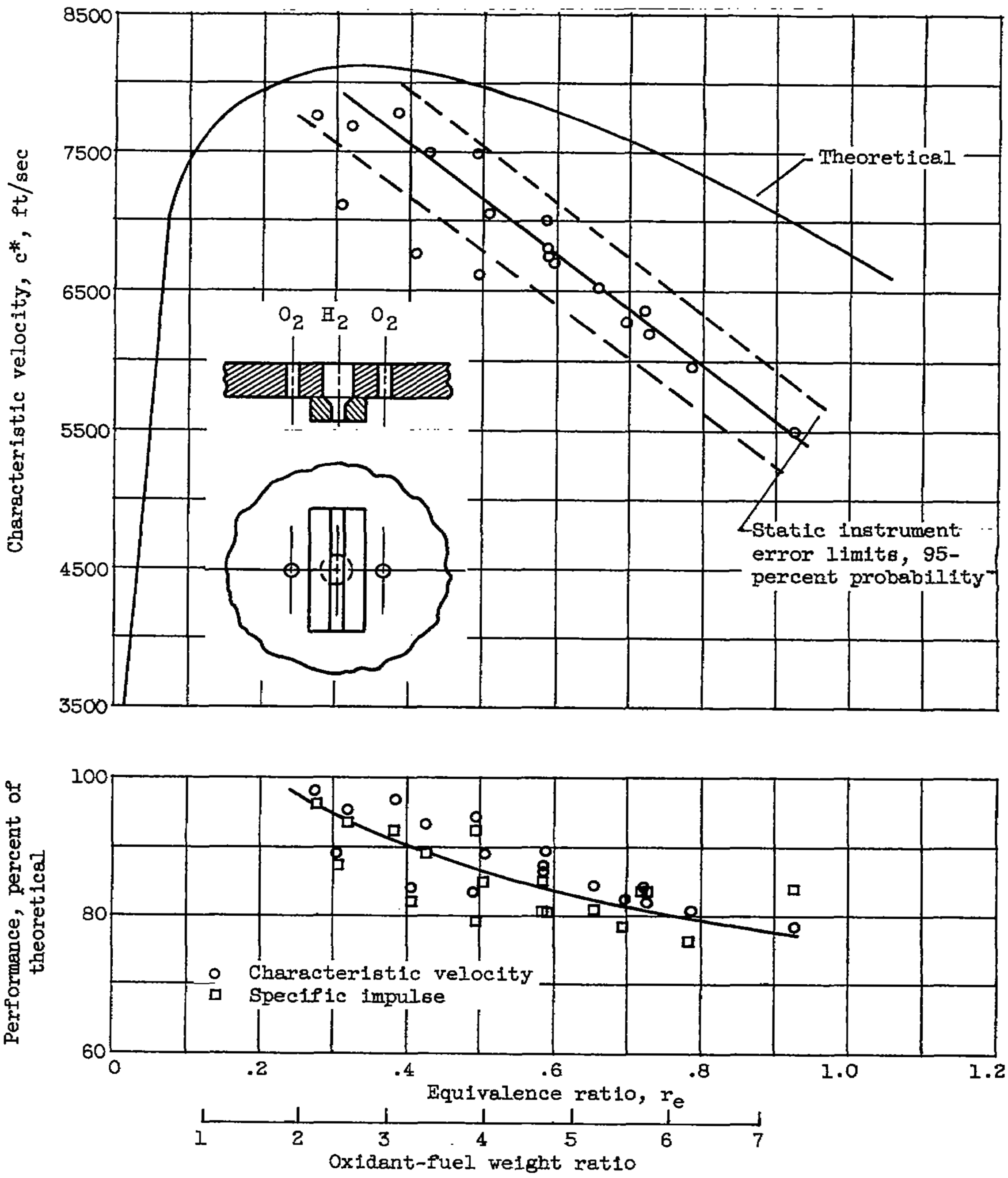


(b) Oxidant-sheets, fuel-jet injector, spreading of oxidant only.

Figure 6. - Continued. Engine performance with combustion chamber having characteristic length of 50 inches.



(c) Fuel-sheet; oxidant-jets injector; spreading of fuel only.

Figure 6. - Continued. Engine performance with combustion chamber having characteristic length of 50 inches.

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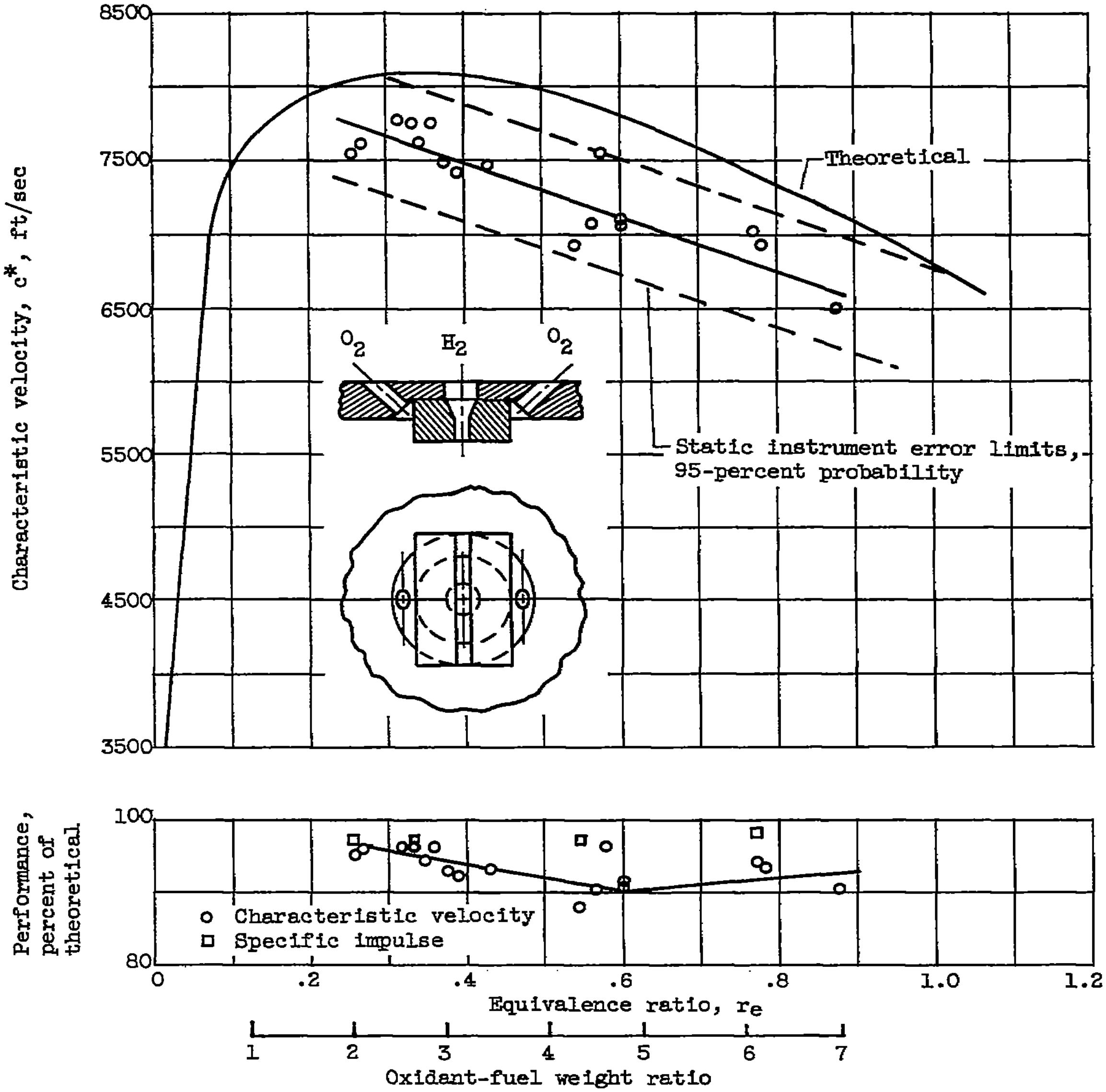

(d) Parallel-sheets injector; spreading of both propellants.

Figure 6. - Continued. Engine performance with combustion chamber having characteristic length of 50 inches.

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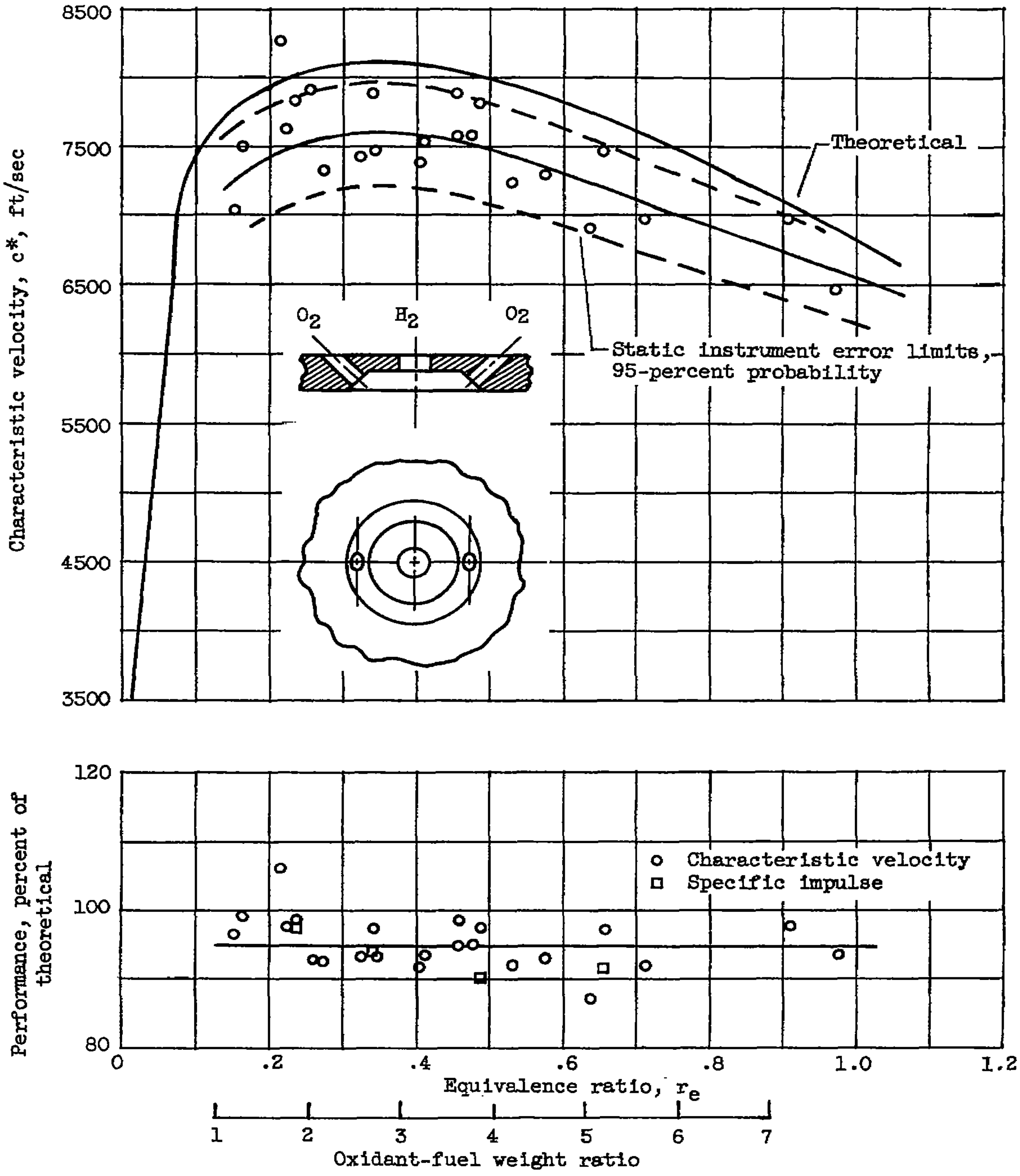

(e) Impinging-jets injector; mixing before spreading.

Figure 6. - Continued. Engine performance with combustion chamber having characteristic length of 50 inches.

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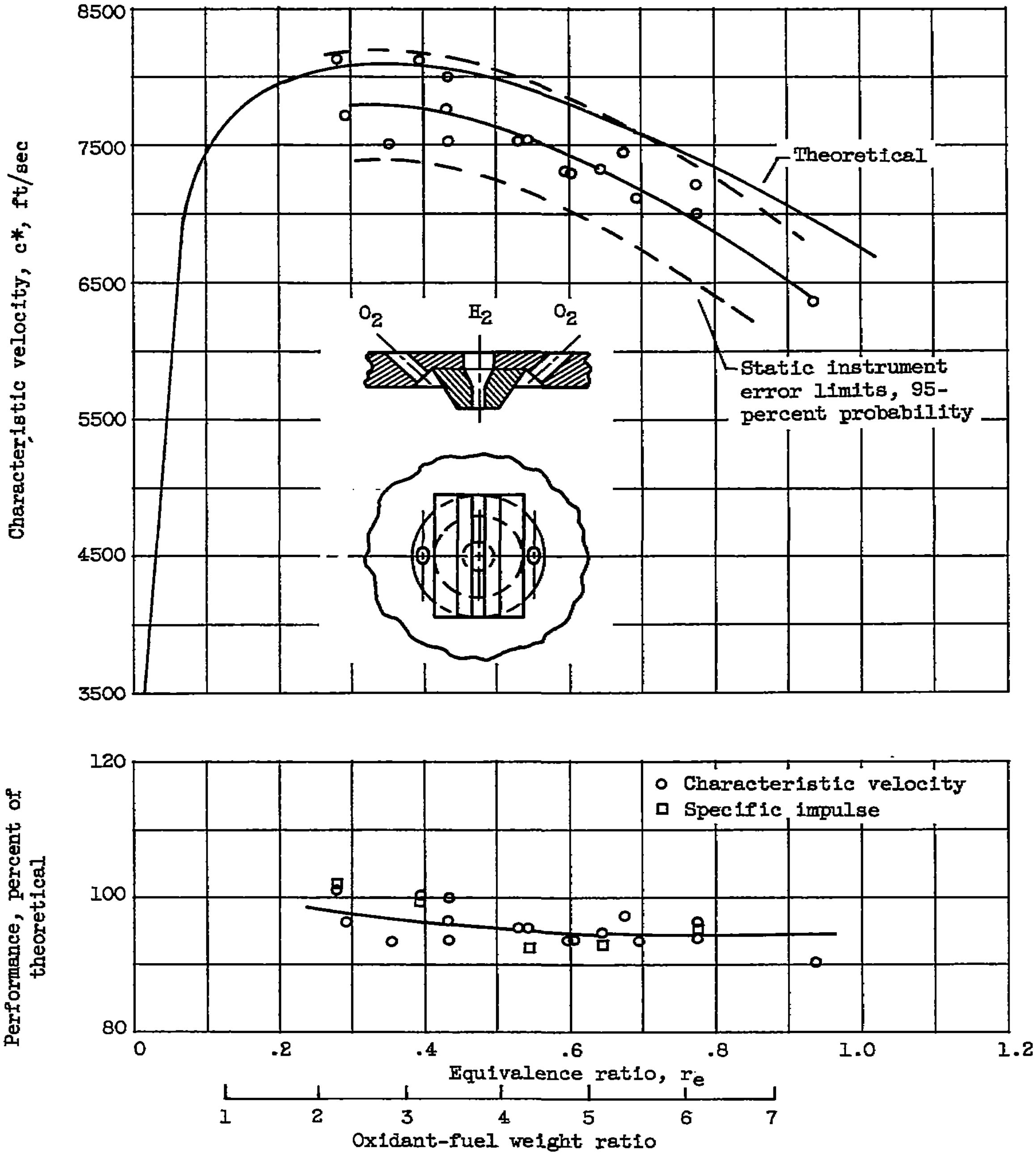
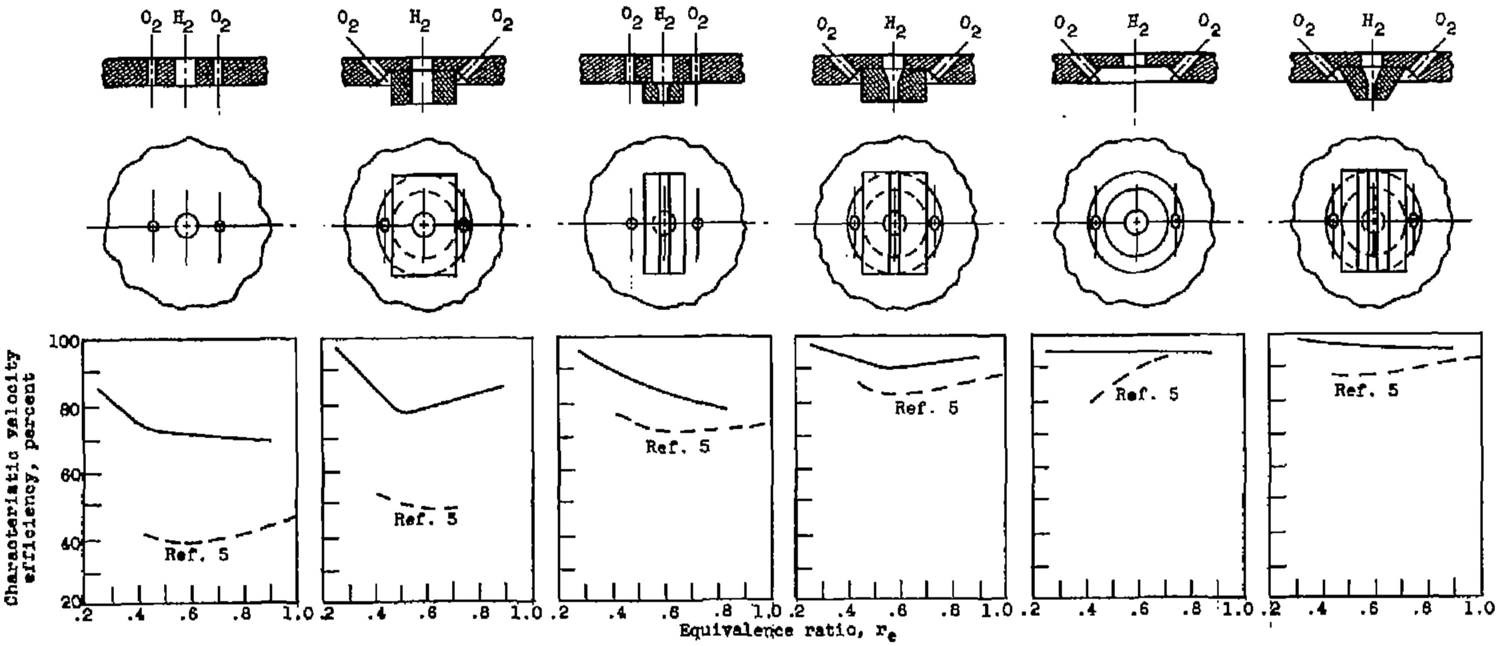


(f) Impinging-sheets injector; mixing after spreading.

Figure 6. - Concluded. Engine performance with combustion chamber having characteristic length of 50 inches.



(a) Parallel jets. Injection without spreading or mixing.

(b) Oxidant sheets; fuel jet. Spreading without mixing.

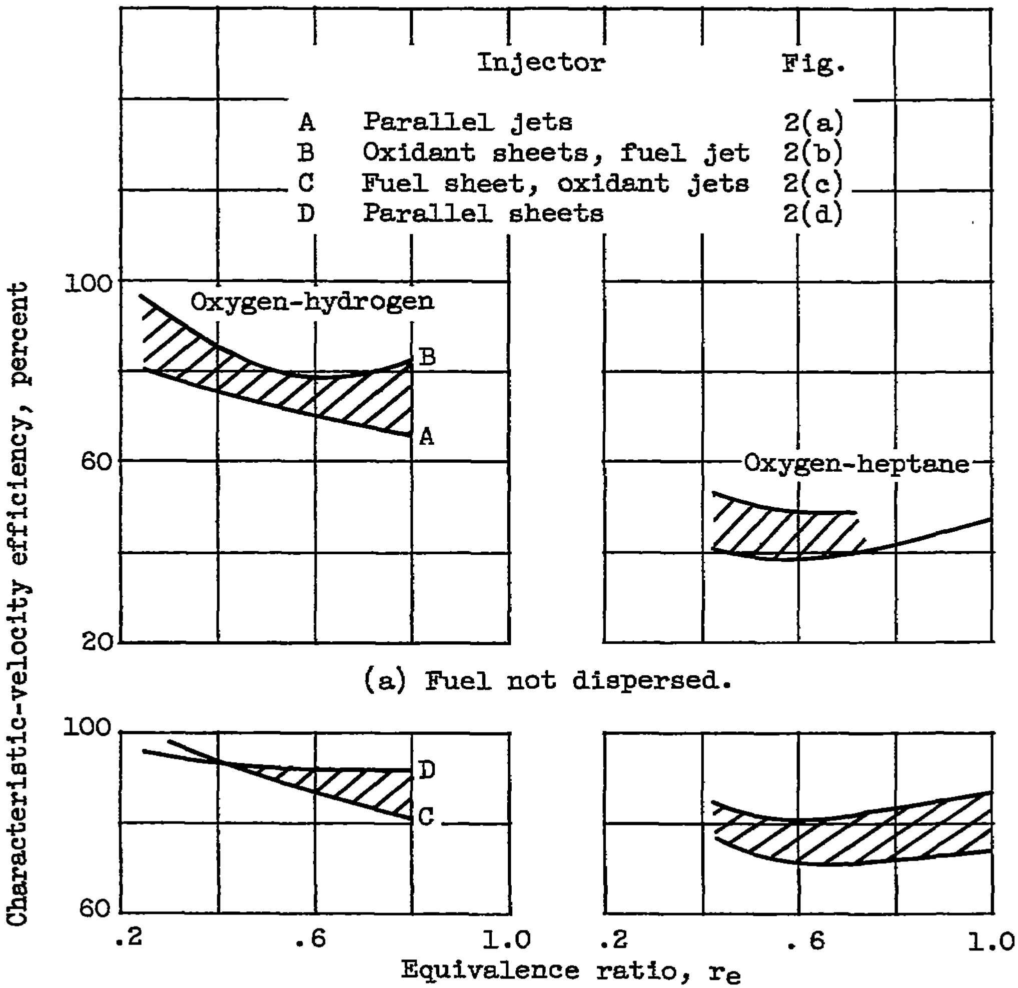
(c) Fuel sheet; oxidant jets. Fuel spreading inside without mixing.

(d) Parallel sheets. Fuel and oxidant spreading without mixing.

(e) Impinging jets. Mixing before spreading.

(f) Impinging sheets. Mixing after spreading.

Figure 7. - Summary performance curves for gaseous hydrogen - liquid oxygen injectors, characteristic velocity performance in 50-inch chamber.



(a) Fuel not dispersed.

(b) Fuel dispersed.

Figure 8. - Effects of oxygen dispersion on performance.

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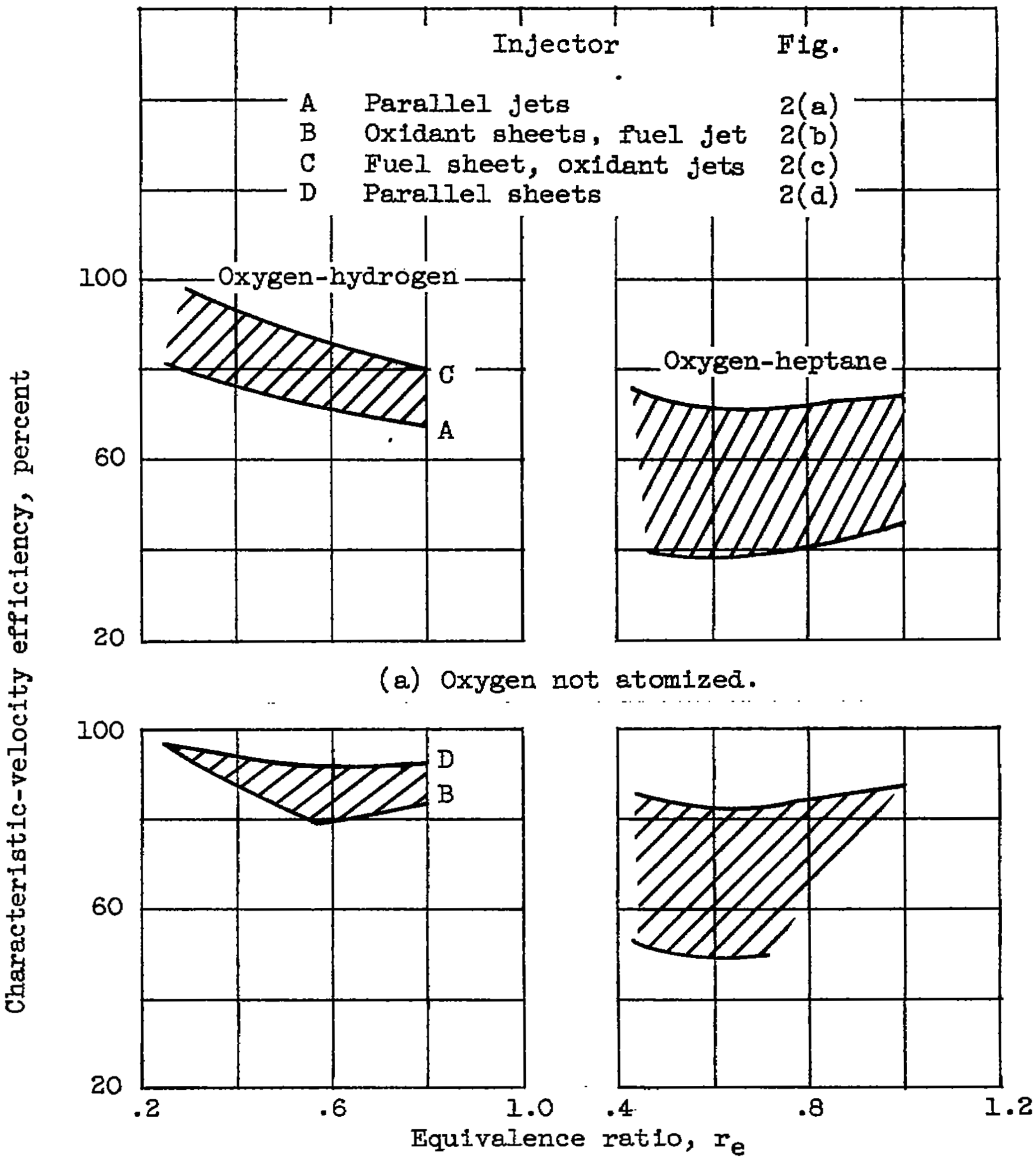
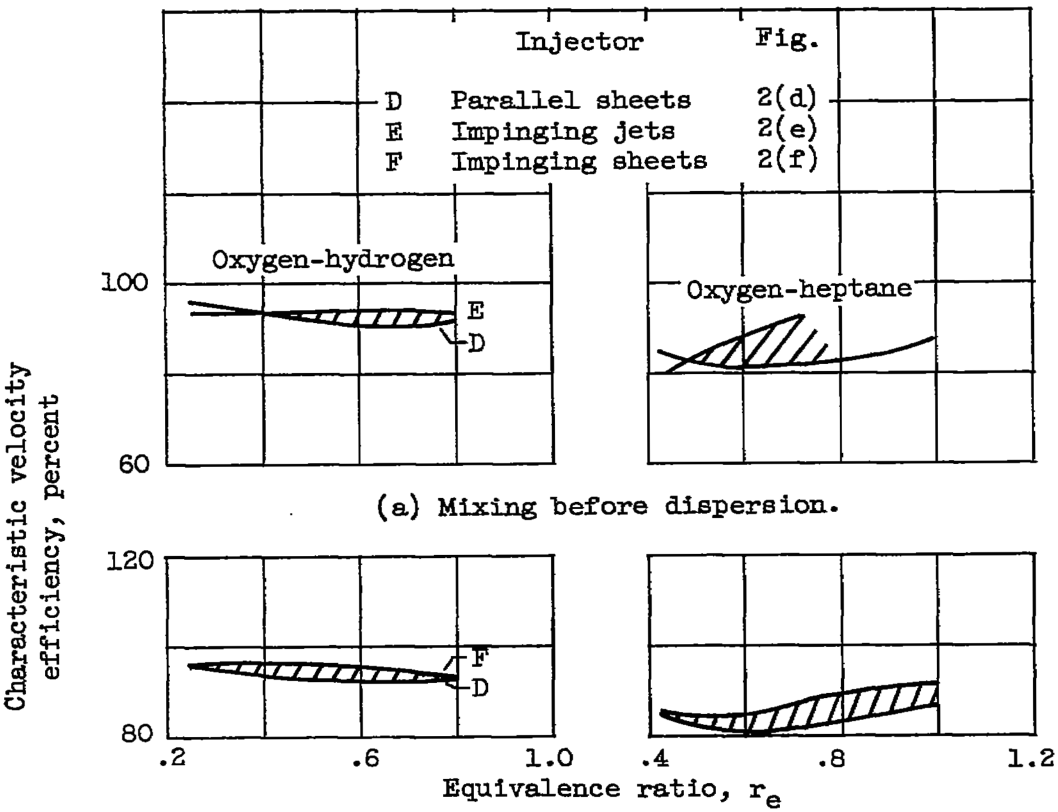


(a) Oxygen not atomized.

(b) Oxygen atomized.

Figure 9. - Effects of fuel spreading on performance.



(b) Mixing after dispersion.

Figure 10. - Effects of propellant mixing on performance.

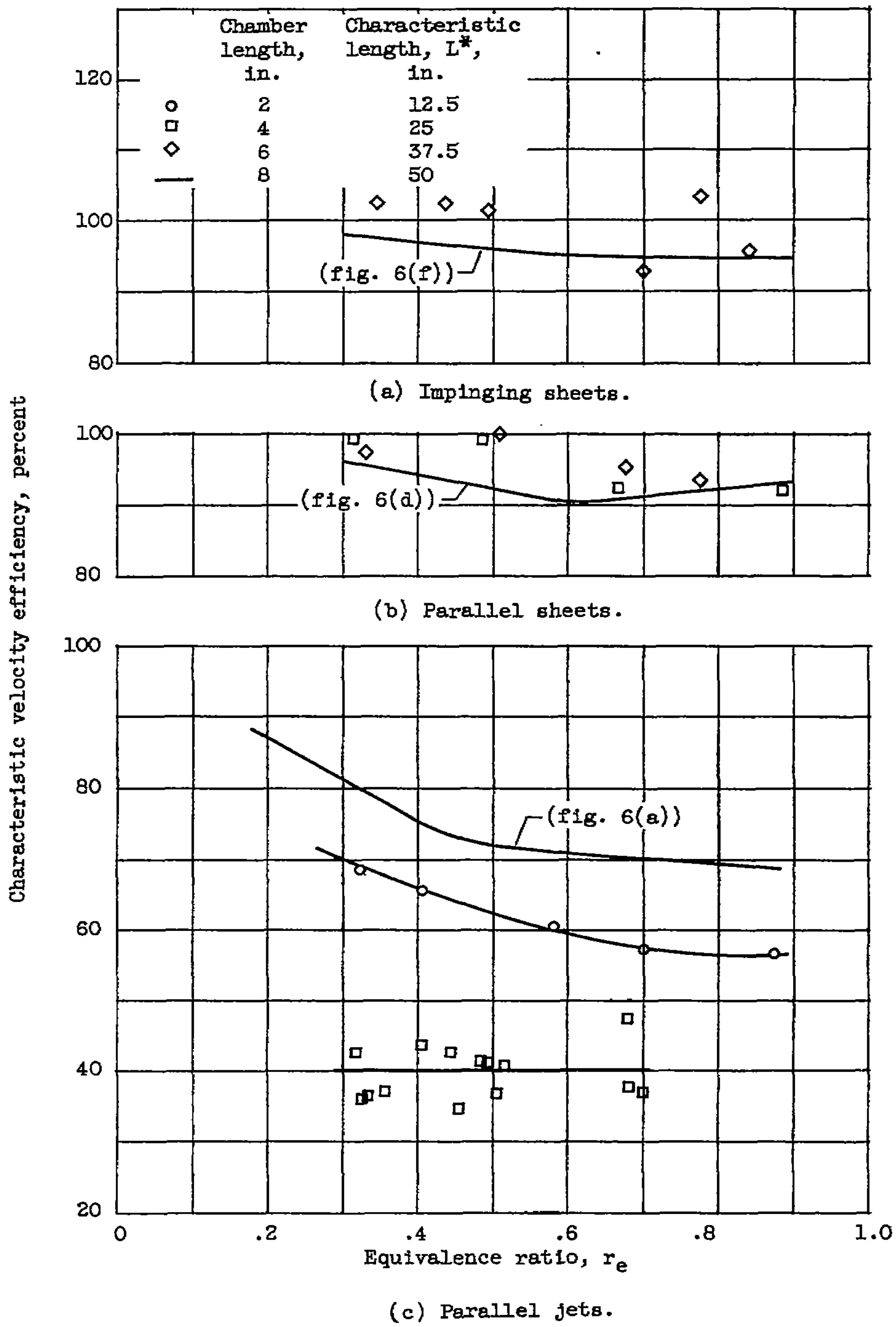


Figure 11. - Short combustion-chamber performance of three injectors compared with performance in a chamber with a characteristic length of 50 inches.

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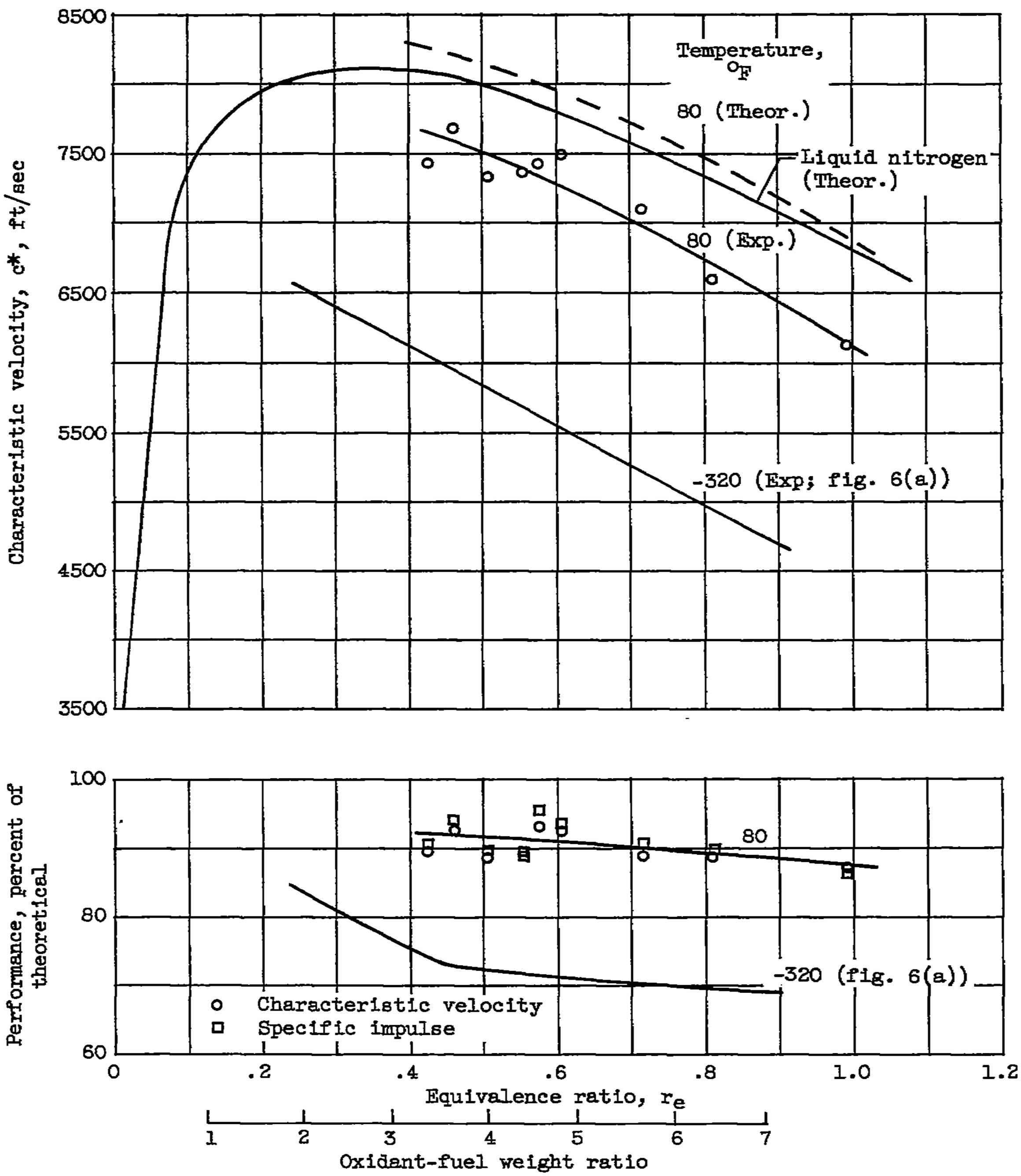

Figure 12. - Effect of hydrogen injection temperature on performance in a parallel-jets injector with chamber characteristic length of 50 inches.

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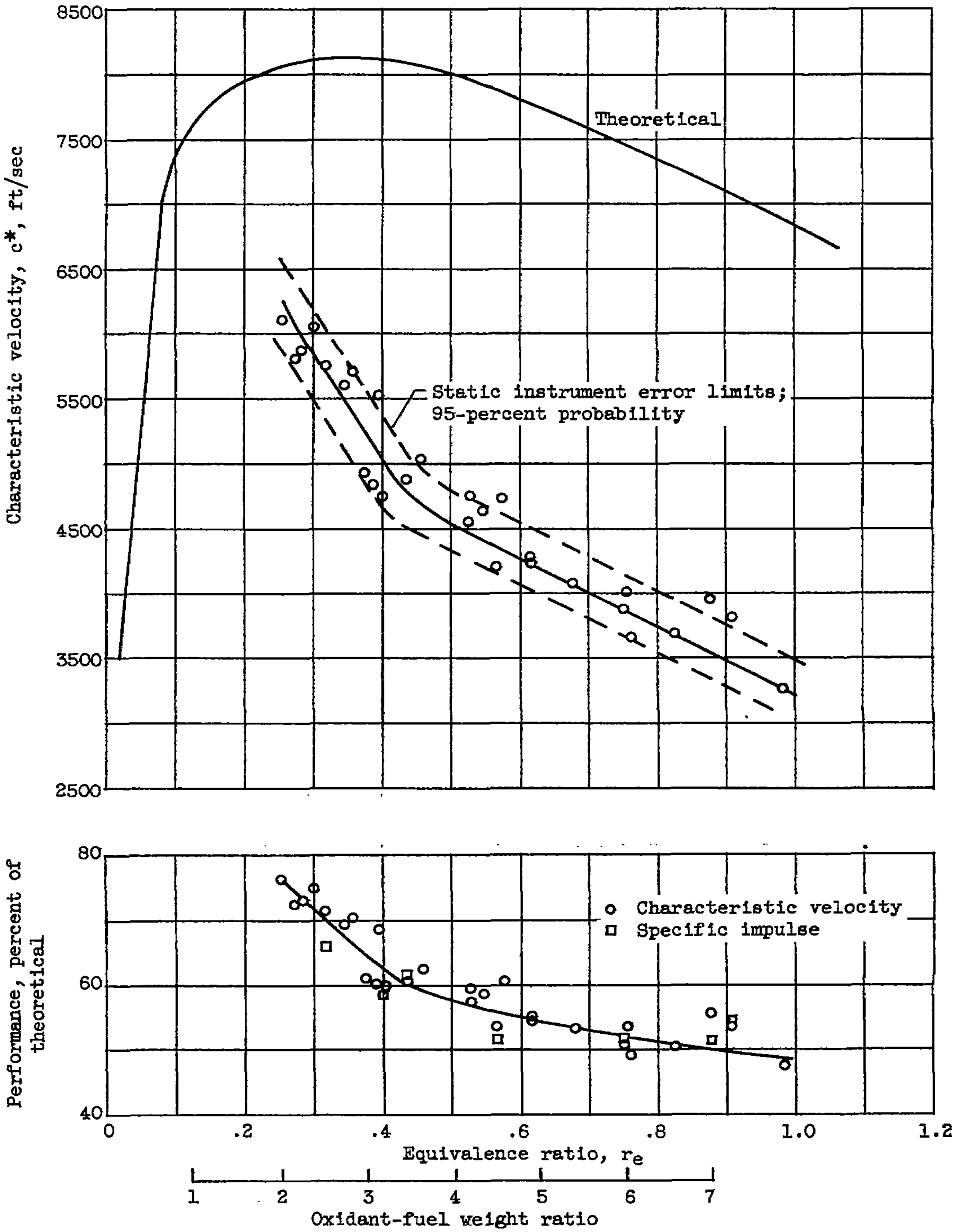

Figure 13. - Effect of fuel placement on engine performance. Chamber characteristic length, 50 inches; fuel-sheet, oxidant-jet injector (fig. 2).

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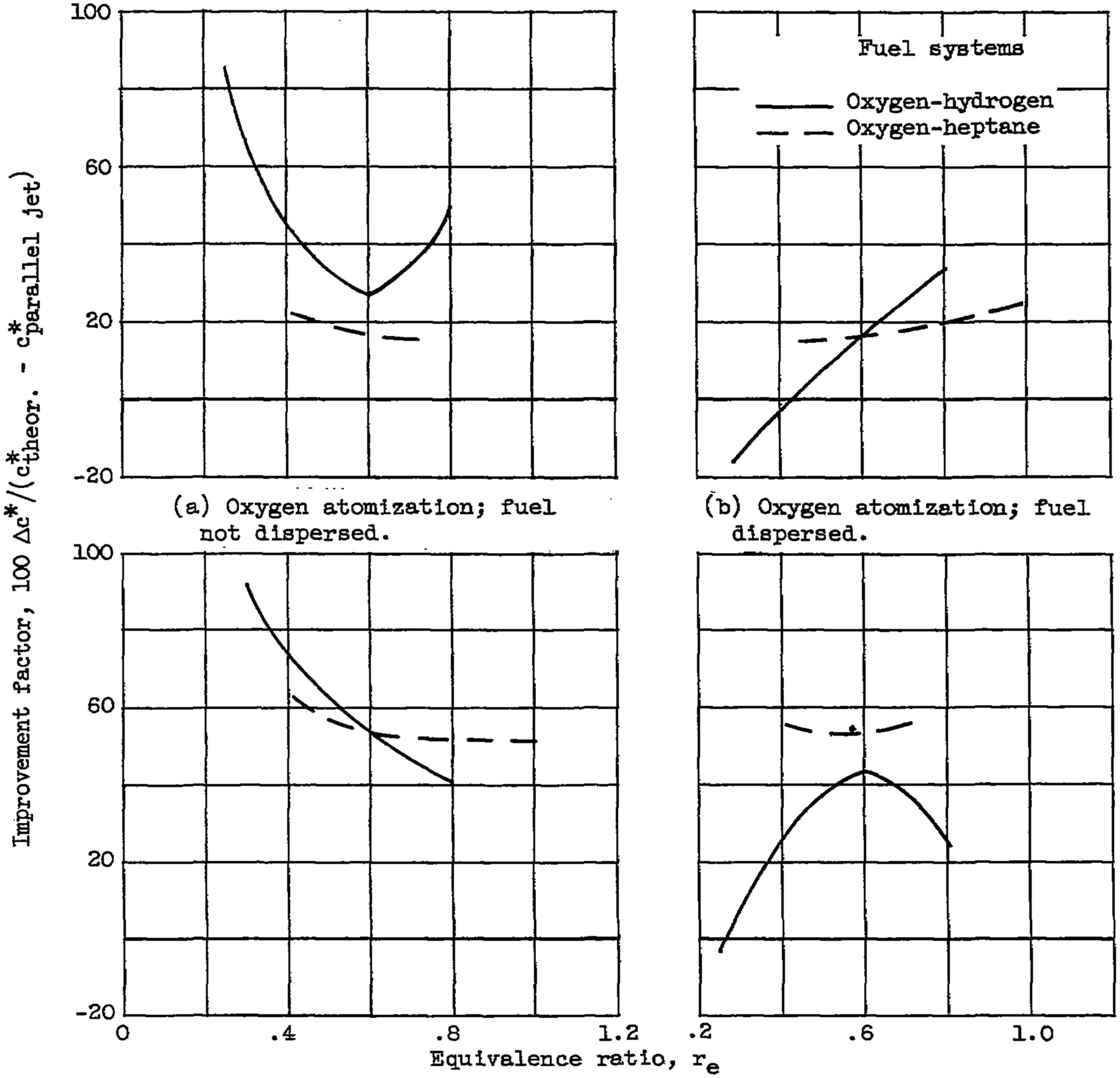

(a) Oxygen atomization; fuel not dispersed.

(b) Oxygen atomization; fuel dispersed.

(c) Fuel dispersion; oxygen not atomized.

(d) Fuel dispersion; oxygen atomized.

Figure 14. - Comparison of propellant preparation effects for oxygen-hydrogen and oxygen-heptane.

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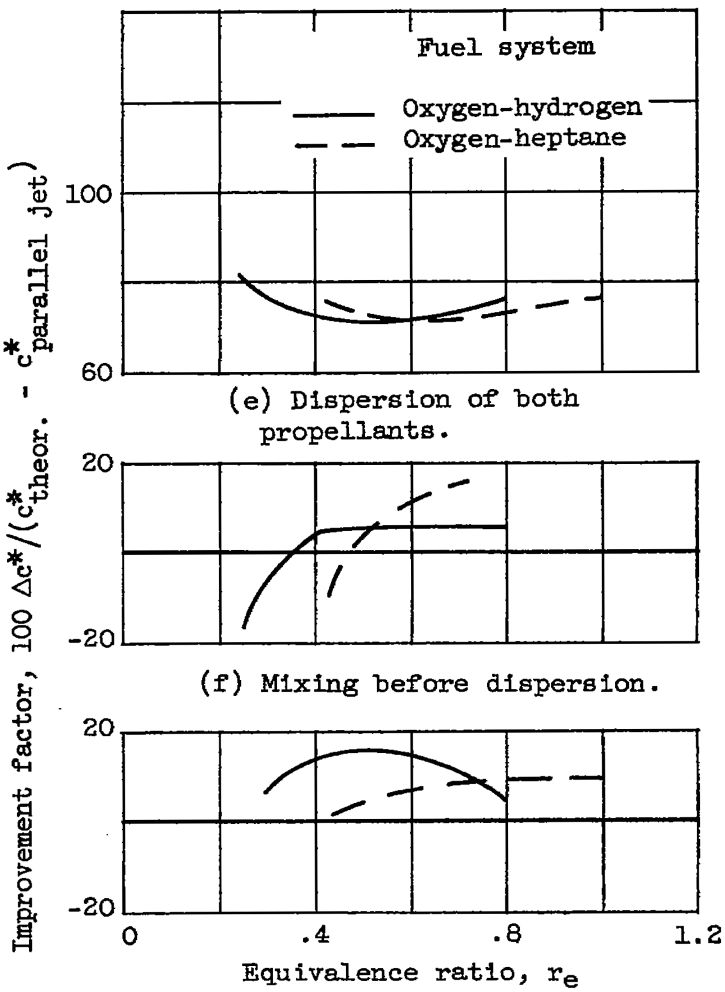

(e) Dispersion of both propellants.

(f) Mixing before dispersion.

(g) Mixing after dispersion.

Figure 14. - Concluded. Comparison of propellant preparation effects for oxygen-hydrogen and oxygen-heptane.

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